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Review and Synopsis of Natural and Human Controls on Fluvial Channel Processes in the Arid West

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Abstract: Parallel to ongoing efforts to revise the U.S. Army Corps of Engineers wetland delineation manual for support of Section 404 under the Clean Water Act, the Corps has initiated an effort to develop an "Ordinary High Water " (OHW) delineation manual. The Arid West region is dominated by watersheds with intermittent and ephemeral dry washes. Consequently, many aquatic resources lack the three characteristic features of a wetland, but they still perform important wetland functions. Arid West channels have recently been described as "ordinary" when they typically correspond to a 5- to 8-year event and typically have an active floodplain with sparse vegetation cover, shifts in soil texture, and occasional alignment with distinctive bed and bank features. With a better understanding of the stream dynamics associated with regulated "ordinary" events, the Corps is now developing OHW functional models for intermittent and ephemeral stream channels of the Arid West. It cannot be adequately determined if a channel has been altered by human disturbances without an understanding of how channels naturally respond to geomorphically effective events and evolve through time. This report provides a literature review of natural and human controls on fluvial processes in the Arid West.

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Preface

This report was prepared by John J. Field, Field Geology Services, Farmington, ME; and Robert W. Lichvar, Remote Sensing/GIS and Water Resources Branch, Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, NH.

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The Commander and Executive Director of ERDC is COL Richard B. Jenkins. The Director is Dr. James R. Houston.

1 Introduction

There are ongoing efforts to update and revise the U.S. Army Corps wetland delineation manual (Wakeley 2002) and to further develop wetland functional models for support of Section 404 under the Clean Water Act (CWA) [33 CFR § 328.3(a)]. A site must have three factors present to be considered a wetland: hydric soils, hydrophytic vegetation, and wetland hydrology (Environmental Laboratory 1987). However, wetlands are only one of several types of "Waters of the United States" (WoUS); others include playas, rivers, and intermittent streams. However, wetlands are the only WoUS type that has a published delineation method, or manual, and for which there are Hydrogeomorphic Method (HGM) models for assessing the quality of wetland functions. Similar delineation manuals and assessment models are needed for the other types of WoUS.

As part of the updating of the Corps wetland manual, the country has been divided into a series of subregions (Wakeley 2002) that generally follow ecosystem boundaries and are similar to those used in the development of hydric soil indicators (Natural Resources Conservation Service 2006). Most areas of the southwestern United States are included as one of the eight subregions in what is referred to as the Arid West (Fig. 1). This region is composed of the arid basins of the southwestern United States, with the higher-elevation mountain areas treated separately as the Western Mountains and Coastal Wetland supplement (U.S. Army Corps of Engineers, in prep.). The Arid West region is dominated by watersheds that have a high frequency of intermittent and ephemeral dry washes, such that many aquatic resources within the watersheds actually lack the three characteristic features of a wetland. Due to arid climatic conditions and the uneven distribution of precipitation events over time, hydric soils rarely develop (Boettinger 1997), the vegetation associated with aquatic resources is characterized by species having multiple adaptive features to survive dry periods and high-salt-content soils (Lichvar and Dixon 2007), and the hydrology is characterized by intense storms with flashy discharge rates (Graf 1988a). Despite these differences, rivers in the Arid West share many of the same functions as rivers in more temperate climates, primarily as conduits for transferring sediment and water through the watershed.

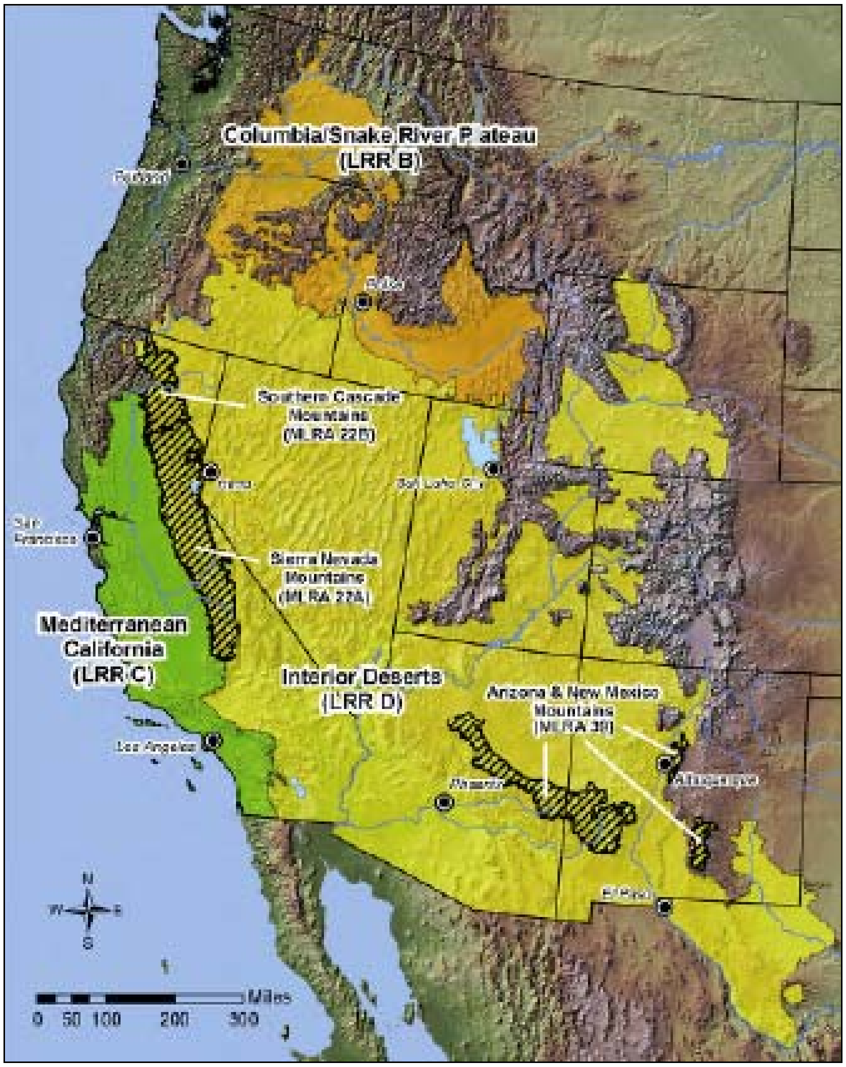


Figure 1. Approximate boundaries of the Arid West Region and subregions (LRR B, C, and D).

The regulatory approach used to delineate WoUS under CWA in the Arid West region relies on the location of physical features associated with stream discharge events or areas of ponded water that are considered "ordinary." Recent efforts by Lichvar et al. (2006), using hydrologic modeling and other remote sensing approaches, have been able to describe relationships between physical features and the outer limits of the Ordinary High Water (OHW) area used to define the regulated limits of WoUS. These efforts show that the majority of previously used physical features for determining the extent of OHW in more temperate climates (Lichvar and Wakeley 2004) are not aligned with the dominant repeating "ordinary" event levels in the Arid West. Lichvar et al. (2006) have described "ordinary" events in Arid West channels as typically corresponding to the

5- to 8-year event, as opposed to the 1- to 2-year event in temperate climates. They also report that the main physical features associated with the ordinary discharge events in the Arid West are the appearance of the active floodplain with sparse vegetation cover, shifts in soil texture, and occasional alignment with distinctive bed and bank features.

With a better understanding of the stream dynamics associated with regulated "ordinary" events, the Corps is now proceeding to develop OHW functional models for intermittent and ephemeral stream channels of the Arid West. These efforts focus on the concepts presented by Lichvar et al. (2006) that the active channel is defined by a suite of natural features forming during geomorphically effective events. Smaller flows leave less distinctive physical evidence within the signature of the last geomorphically effective, or ordinary, event. Lichvar et al. (2006) developed a working conceptual model for the active floodplain that incorporates the natural disturbances of erosion and deposition within the active channel until the next geomorphically effective event removes these less distinctly developed features within the channel and begins a new cycle of floodplain formation. Understanding this cyclic set of responses is critical to evaluating the functions and "health" of an OHW reach in the Arid West. Determining if a channel has been altered by human disturbances cannot be adequately assessed without an understanding of how channels naturally respond to geomorphically effective events and evolve through time between such large flood events.

This report provides a literature review of natural and human controls on fluvial processes in the Arid West with the purpose of identifying and describing channel responses to natural disturbances and how human activities might alter these natural processes. By better understanding these channel dynamics and how human influences alter the physical conditions of the channel, we can develop functional models to assess the quality of OHW aquatic resources. After a brief synopsis and update of earlier literature reviews that focused on identifying the Ordinary High Water Mark (OHWM) in the Arid West (Field 2004a, 2004b), this report will describe natural cycles of channel evolution observed in the Arid West and discuss how common human riverine land uses can alter channel morphology, particularly on arid-region rivers. For the purposes of this report, the "Arid West" is defined to include all or portions of eleven arid to semiarid western states: Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Texas, Utah, Washington, and Wyoming (Fig. 1).

This regional supplement is applicable throughout the highlighted areas, including coastal areas, with the following exceptions:

- The cross-hatched portions of LRR D comprising the Sierra Nevada Mountains (MLRA 22A), the Southern Cascade Mountains (MLRA 22B), and the Arizona and New Mexico Mountains (MLRA 39); and
- Other embedded mountain ranges not indicated on the map that support predominantly coniferous forests with interspersed meadows, shrublands, and riparian woodlands above and including the ponderosa pine zone.

2 Hydrological Conditions and Fluvial Processes

Literature reviews on hydrological conditions and fluvial processes were previously completed to better understand how the physical expression of the OHWM and methods for identifying the OHWM might vary in the Arid West compared to the more temperate climates of the eastern United States, where methods for delineating the OHWM were originally developed (Field 2004a, 2004b). The findings of these earlier reviews are summarized below, with relevant literature from the past three years added as appropriate.

Hydrological Conditions

The Arid West comprises several climatic, physiographic, and ecological subregions with varying precipitation source areas, watershed characteristics, and vegetation patterns. These factors combine to impact the amount of precipitation that becomes surface runoff in streams. Precipitation in the Arid West is derived from three distinct storm types whose relative importance varies spatially and from year to year throughout the region: winter North Pacific frontal storms, summer convective thunderstorms, and late summer eastern North Pacific tropical storms (Ely 1997). Summer thunderstorms are enhanced by the North American Monsoon in Arizona and New Mexico as moisture is drawn in at high elevations from the Gulf of Mexico and at low elevations from the Gulf of California owing to the poleward retreat of the North Pacific storm track during the summer (Higgins et al. 2003). The El Niño/Southern Oscillation Index (ENSO) exerts a strong decadal-scale influence, leading to greater winter precipitation in California (Schonher and Nicholson 1989) and greater fall and spring precipitation in Arizona and New Mexico (Andrade and Sellers 1988).

Several precipitation and watershed characteristics exert a strong influence on rainfall–runoff patterns in arid climates, including the spatial and temporal variability of rainfall, rainfall interception, evaporation and transpiration, and channel transmission losses (Vivoni et al. 2006). In many deserts, particularly where precipitation intensities are high, the runoff hydrograph characteristically rises very steeply as the result of

limited infiltration capacity and then falls sharply in response to transmission losses (Cooke et al. 1993). Rainfall–runoff models developed specifically for arid regions can more accurately account for transmission losses and other conditions characteristic of arid regions (Sharma and Murthy 1998). Other processes important to account for in rainfall–runoff modeling of arid regions are soil moisture storage, spatial distribution of rainfall, evaporation, and groundwater recharge (Niemczynowicz 1990). Recent detailed analysis of a storm event on an ephemeral tributary to the Rio Grande showed that only 3.6 percent of the rainfall resulted in runoff with 49 percent of the flood volume lost to a shallow aquifer (Vivoni et al. 2006). Rainfall–runoff models that account for these various hydrological conditions are more reliable for use in arid regions, as they will better predict the magnitude and duration of the storm hydrograph generated from a given precipitation event. Models that generate a storm hydrograph, as opposed to just estimating flood peaks, will likely prove more valuable for delineating the OHW channel, since flow duration as well as peak discharge exerts a strong influence on channel morphology.

Three flow types dominate ephemeral stream processes in the Arid West: channelized flow, sheetfloods, and debris flows. For a given discharge, hydraulic models are able to reliably predict flow velocity, depth, and width for channelized flow conditions but are less capable of characterizing sheetfloods and debris flows. Sheetfloods and debris flows exert a strong influence on the morphology of some fluvial landforms, such as alluvial fans (Field 1994, Blair and McPherson 1992), while the most frequently occurring process, channelized flow, may have limited morphological impact. Consequently, accurately characterizing flow conditions on arid-region stream systems, particularly alluvial fans, may depend on combining hydraulic modeling with remote sensing and geomorphic mapping techniques (Pelletier et al. 2005).

Geomorphological Conditions

While perennial, single-thread, meandering channels typical of humid regions do occur in the Arid West, four other stream system types are also present: discontinuous ephemeral streams, compound channels, alluvial fans, and anastomosing streams. (A more thorough discussion of these arid-region stream types is provided below in the discussion on natural channel evolutionary cycles of desert stream systems.) Common to all four stream types is their pronounced spatial and temporal variability in channel morphology. Consequently, physical features found along a

channel will vary between stream types, along the length of any given stream, and through time at a single point. Understanding this transitory nature of channel morphology along desert rivers and the general tendency towards establishing a channel adjusted to the low flow condition is important for developing models of channel evolution that can be used to recognize human-induced disruptions to natural conditions. However, the natural sensitivity of arid-region river channels to flow variability, coupled with a wide discrepancy in arid regions between record peak and average annual peak flows, results in a state of perpetual disequilibrium (Tooth and Nanson 2000a), further complicating efforts to distinguish between natural and human-induced channel adjustments.

3 Natural Cycles of Channel Evolution

Stream channels are not static features on the landscape. They adjust to changing watershed conditions and evolve through time. An initial disturbance, or perturbation, significant enough to precipitate a channel response is often followed by a series of channel adjustments that bring the stream channel back into equilibrium. If the perturbation creates a permanent change to watershed conditions, such as in an urbanized setting, the channel will establish an equilibrium condition different from what existed prior to the disturbance. For perturbations that alter the sediment and water delivery to the channel in the same way (e.g., urbanization and natural increases in rainfall intensity would both increase peak flows), a similar series of channel adjustments is likely to occur along the same stream type under similar geological, physiographic, and climatic conditions. Where a repeatable pattern of adjustments has been documented in multiple locations, channel evolutionary models have been developed that can be used to anticipate future changes along channels that have only recently been disturbed. The tendency of streams to re-establish equilibrium through channel evolutionary processes is essential for sustaining healthy stream function and efficient sediment transport through the watershed despite occasional disturbances.

Channel evolutionary models have been developed, or can be derived from existing research, for single-thread, meandering, humid-region rivers and for four additional stream system types typical of arid regions: discontinuous ephemeral streams, compound channels, alluvial fans, and anastomosing streams. The conditions under which each stream type develops and the channel evolutionary model that describes the sequence of adjustments that follow certain disturbances are discussed below.

Meandering Rivers

Single-thread, generally meandering channels with adjacent floodplains are characteristic of humid climates. They do occur in desert climates where a dependable water supply is present, as is associated with allogenic rivers (i.e., rivers that drain watersheds extending into more humid climates) (Graf 1988a, Tooth 2000) (e.g., Colorado River). Meandering develops in response to a river's tendency to minimize the amount of change occurring at any one point along the river (Langbein and Leopold

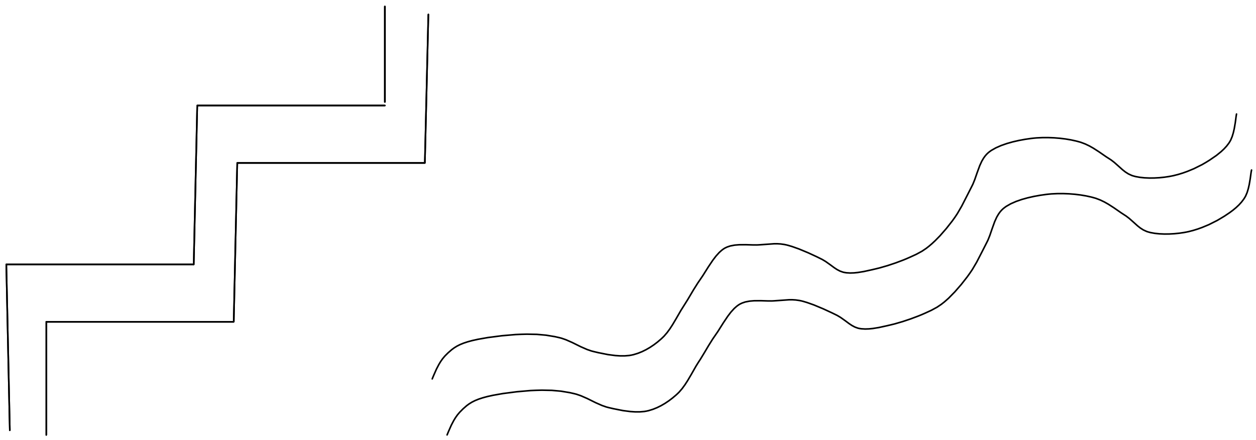


Figure 2. Unstable river planform in erodible materials (left) that will evolve into a stable meandering form (right) through time in order to minimize the amount of turning that occurs at any one point.

1966). Rivers are less stable, for example, at a right-angle bend (Fig. 2a), because of the excess energy expenditure that would occur at the sharp turn. If erodible materials are present in the bank, such a sharp bend would be expected to recede through time, resulting in a minimization of turning and energy expenditure at any one point (Fig. 2b). Ultimately, the characteristic stable meandering planform of humid-region rivers develops (Fig. 3). A disturbance along a meandering river that results in a focusing of energy expenditure at certain points will lead to a series of adjust-

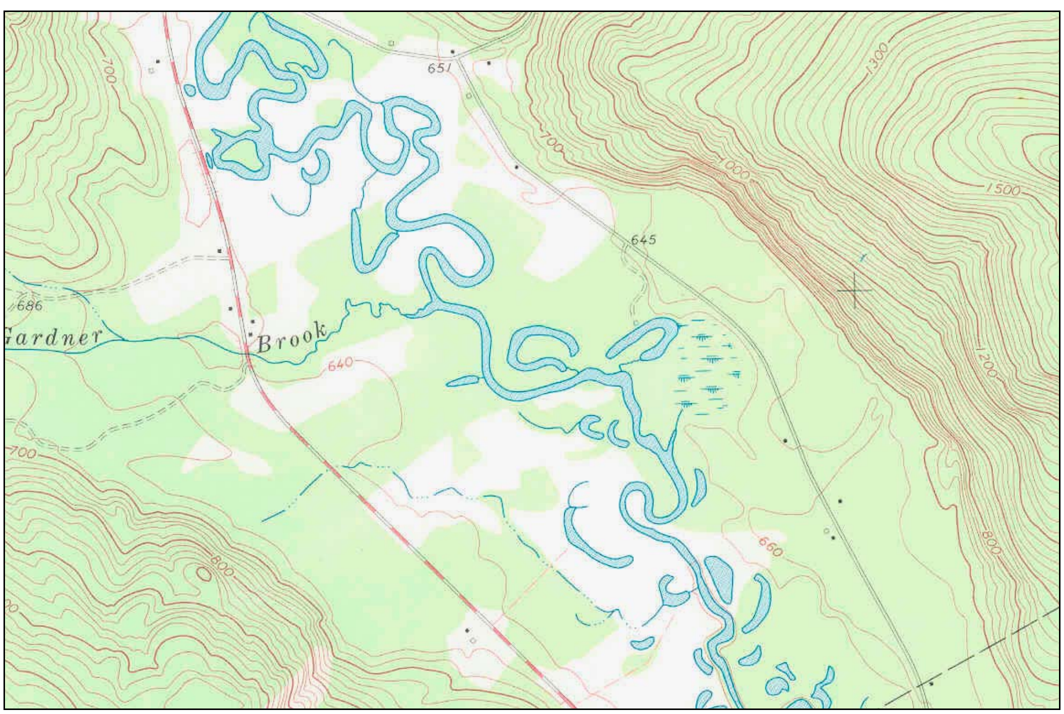


Figure 3. Topographic map of a portion of the Ellis River in Maine, showing a meandering planform that is typical of humid-region rivers.

ments that once again minimize energy expenditure throughout the stream system and re-establish an equilibrium condition. The minimization of change from one point to the next ensures that the sediment transport capacity through the river is maintained, so sediment being carried in the river does not accumulate rapidly nor do the bed or banks erode rapidly.

A distinct series of channel evolutionary processes result when rivers experience a disturbance that creates disequilibrium and leads to channel incision (Fig. 4) (Schumm et al. 1984, Simon and Hupp 1986, Elliot et al. 1999, Schumm 2005). Channel incision generally results when the sediment transport capacity of a stream reach is elevated relative to the sediment supplied to the reach. Such changes can result from a number of natural and human-induced conditions, including climate change, reforestation, urbanization, upstream dams, channel constrictions, and bank armoring. Humid-region rivers, with the increased bank resistance afforded by riparian vegetation, initially respond to an increase in sediment transport capacity by eroding, or incising, the channel bed (Fig. 4b). With incision, the magnitude of flow needed to overtop the channel

banks can be dramatically increased such that greater stream power is focused in the stream channel rather than dissipated across the wider floodplain. The incision process is, at first, self-enhancing, because the concentration of flow in the channel leads to further bed degradation. Ultimately, however, the banks become unstable as they are undercut and oversteepened, potentially undermining vegetation or riprap placed on the bank to provide bank resistance.

The channel begins to widen with bank destabilization, and a new phase of the channel evolutionary process begins (Fig. 4c). As the widening progresses, the flow energy in the channel becomes spread out over a greater area, and eventually the stream loses its capacity to remove sediment from the base of the eroding banks. Larger and larger flows become necessary to enlarge the channel further, so processes that lead to bank stabilization and channel aggradation have greater influence. The steep vertical banks slowly slope back as material sloughs off the top of the bank and accumulates at its base without being fully removed. The banks become further stabilized as vegetation takes hold on the more gently sloped streambanks.

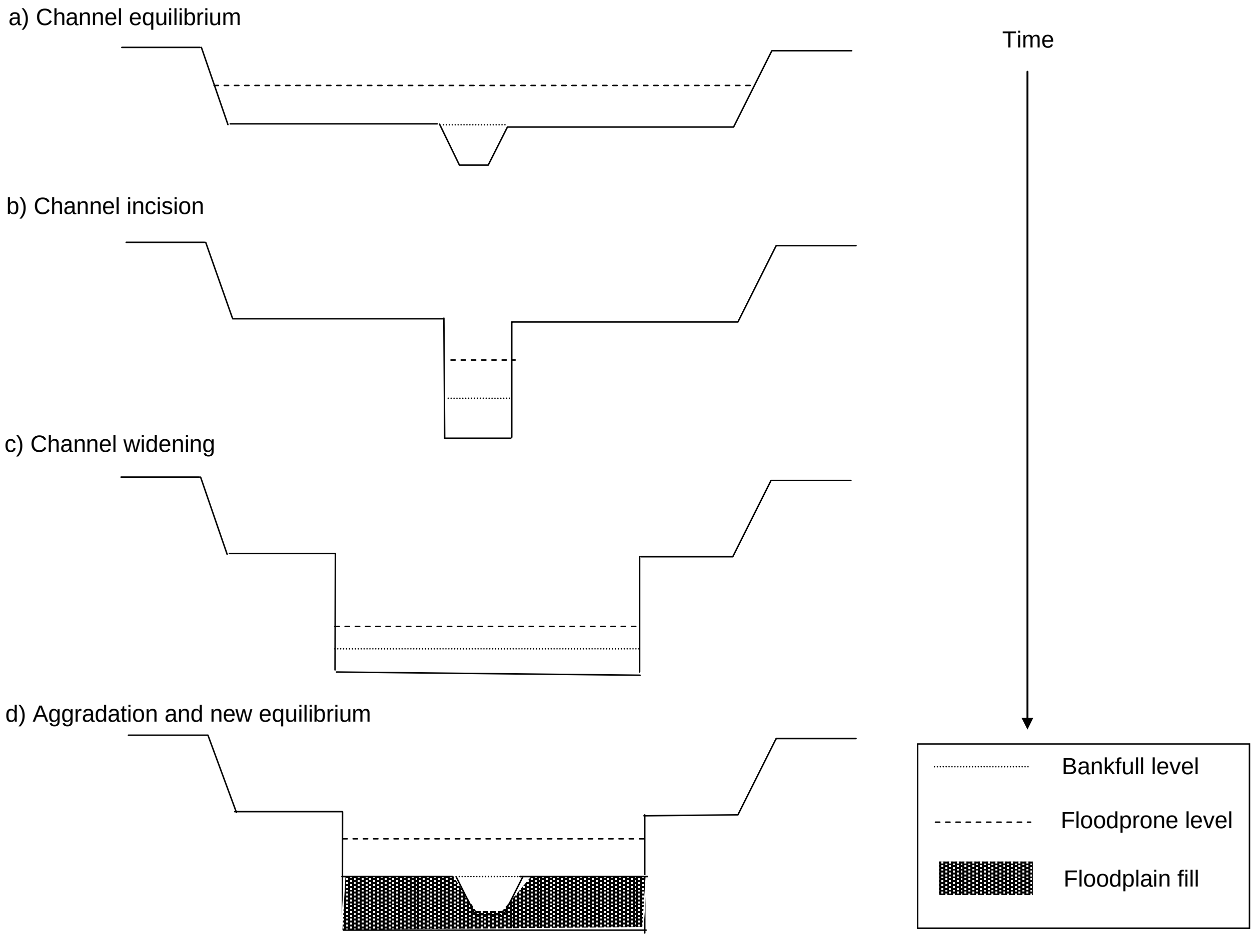


Figure 4. Simplified channel evolution model of how a stream responds to incision. Each stage is described further in text. The bankfull level and the floodprone level are defined in Rosgen (1996). Note that the banks of actual stream channels are more rounded than shown.

The reduction in gradient resulting from incision, the greater cross-sectional area produced by widening, and the higher hydraulic roughness accompanying revegetation of the banks all lead to a reduction in the sediment transport capacity. No longer capable of transporting sediment through the incised and widened reach, channel aggradation ensues (Fig. 4d). Channel meanders develop around gravel/sand bars that form in the channel. As vegetation colonizes the bars, additional fine material is trapped on the bar surface, a new floodplain is built, and the channel achieves a new equilibrium condition, marking the end of the channel evolutionary process and a return of the channel and floodplain functions that existed prior to incision.

The new floodplain level may be inset below the original floodplain surface if permanent changes to watershed conditions have occurred (Fig. 4d). The lower gradient of the newly established floodplain and channel (a

consequence of being inset below the former floodplain level) reflects reductions in sediment delivery to the channel or increases in sediment transport capacity. If the watershed disturbances are only temporary, perhaps reflecting cyclic climate changes related to El Niño events, the new floodplain level will re-establish at nearly the same elevation that existed prior to the disturbance.

Rosgen (1996) presents a channel classification scheme where channels are assigned a letter designation between A and G based largely on the numbers of flow paths, degree of flow confinement, channel width:depth ratio, and sinuosity. Channels with access to a floodplain and limited flow confinement are designated "E" channels when their sinuosity is high and width:depth ratios low and "C" channels when sinuosity and width:depth ratios are not as extreme. Confined channels where flood flows cannot access a floodplain are designated as "G" channels when width:depth ratios are low and "F" channels when the width:depth ratio is higher. The Rosgen method can be used to describe a sequence of changes in channel type similar to the channel evolutionary process described above. With incision, a "C" or "E" channel is converted to a narrow "G" channel due to increased flow confinement accompanying floodplain abandonment. As the "G" channel begins to widen, the width:depth ratio increases until an "F" channel develops. When channel aggradation successfully creates a new floodplain or reconnects the channel with the former floodplain, a "C" or "E" channel re-emerges, channel equilibrium is restablished, and channel evolution is completed. A braided, or "B" type, channel may be present during the initial phases of aggradation.

A large determinant on the rate and scale of incision, and subsequent evolution of the channel, is the composition of the banks. Less-cohesive sandy soils are easily undermined and collapse at shallower depths, so bank widening ensues sooner and channel evolution occurs more quickly (Schumm 2005). Conversely, banks composed of more-cohesive clay-rich soils are more resistant to bank erosion, lead to greater incision depths, and complete the evolutionary process slower. The added resistance of bank vegetation can slow the rate of bank widening significantly, even where non-cohesive soils are present. Climate is also an important control on the rate of channel evolution. The complete evolutionary process can occur in a matter of decades in the temperate climates of the southeastern United States (Schumm 2005) in one locality while taking over a century in portions of the Arid West (Waters and Haynes 2001). In general, the

incision phase (Fig. 4b) transpires much more rapidly than the widening (Fig. 4c) and aggradation (Fig. 4d) stages (Simon and Rinaldi 2006).

Once channel evolution is complete, humid-region rivers, with the added resistance and roughness of bank vegetation, are more capable of resisting the erosive forces of large flood flows, while trapping additional debris and sediment on the floodplain. This leads to the vertical accretion of the floodplain surface. With a well-established floodplain to attenuate larger storm discharges, channel dimensions and, therefore, stream function are less likely to be dramatically altered by extreme events. Erosive forces in the channel are minimized and can be resisted by vegetative growth on the banks. Consequently, bank erosion rates are low and equilibrium channel dimensions can be maintained as a meandering channel migrates slowly across the floodplain. Arid-region rivers, in contrast, remain sensitive to extreme discharges, even after a period of channel evolution, because bank resistance remains limited given the lack of vegetation and the abundance of sandy soils.

Discontinuous Ephemeral Streams

Rivers in desert climates, with less vegetative resistance on the banks, are less likely to develop vertically accreted floodplains and meandering planforms, so alternative mechanisms for minimizing energy expenditure from point to point emerge. Processes of channel evolution following a watershed disturbance differ for each stream type, although similarities exist in the models that describe these processes. Discontinuous ephemeral streams form a distinctive stream pattern, common throughout the Arid West, characterized by alternating erosional and depositional reaches (Fig. 5) (Schumm and Hadley 1957, Patton and Schumm 1975, Bull 1997, Field 2001, Pelletier and DeLong 2004). Flow energy and sediment is dissipated across the sheetflood zones as flow expands. Flow reconcentrates at the downstream end of the sheetflood zones. Erosional channels develop where the sediment transport capacity of the sediment-free water flowing off of the sheetflood zones has crossed a critical threshold level (Bull 1979) and can erode the surface.

Discontinuous ephemeral streams are best developed in semi-arid climates, because the sediment yield is high (Tooth 2000), sufficient vegetation is present to trap sediment on the sheetflood zones (Packard 1974), and transmission losses reduce the stream's ability to transport the sediment through the system (Bull 1997, Reid and Frostick 1997, Tooth 2000).

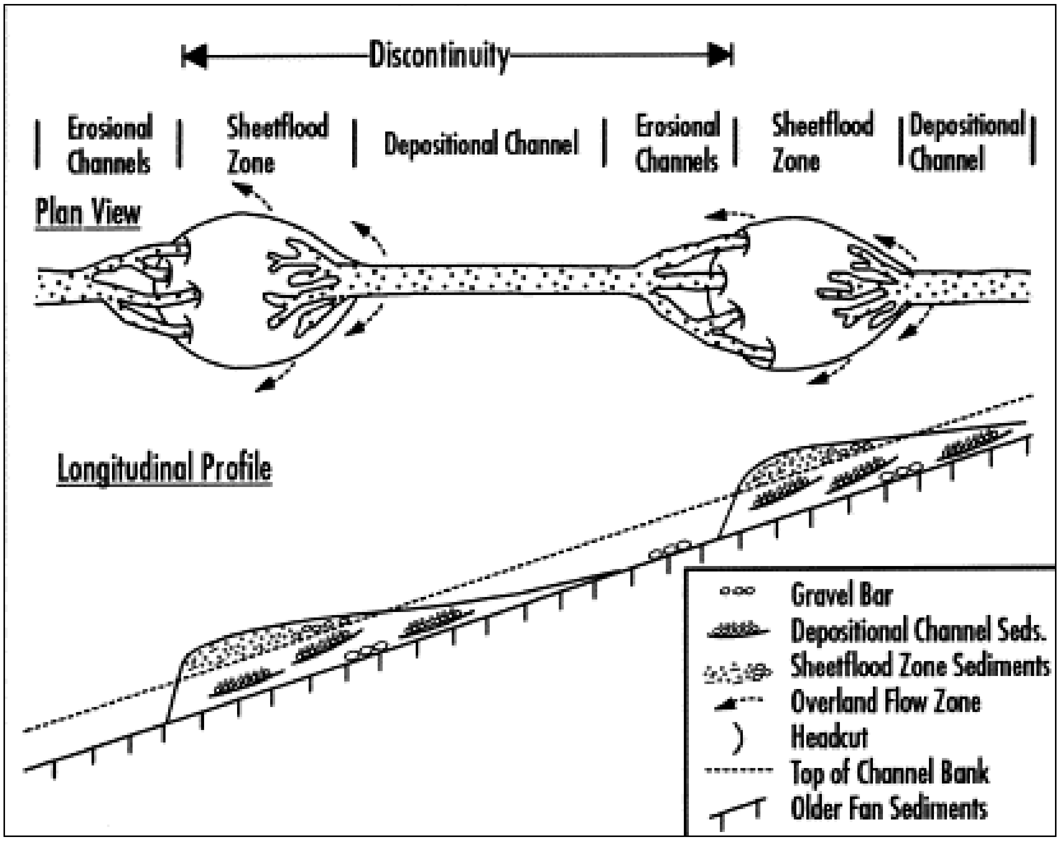


Figure 5. Schematic plan view and longitudinal profile of a discontinuous ephemeral stream system. (From Field 2001.)

Consequently, sediment has a tendency to move through discontinuous ephemeral streams episodically (Schumm and Hadley 1957), likely as a series of waves (Lekach and Schick 1983, Schick et al. 1987, Graf 1988a, Pelletier and DeLong 2004). Given the external climatological and hydrological constraints of semi-arid regions, discontinuous ephemeral stream systems represent the most efficient channel pattern for transporting sediment through the watershed and sustaining river function.

The longitudinal distribution of processes and morphologies along one discontinuity (Fig. 5) can be repeated multiple times along a stream, with the length of individual discontinuities ranging from 15 m to over 10 km, depending on drainage area (Bull 1997). The morphological changes observed in a downstream direction along discontinuous ephemeral stream systems (Fig. 5) are the same changes that occur at a single point through time as the channel evolves. Channel backfilling caused by the headward migration of aggradational reaches can transform a deep channel into an area of sheetflooding over periods of tens to hundreds of years (Bull 1997). The build-up of slope resulting from aggradation ultimately

leads to retrenching of the same area once sediment concentrations fall below the threshold necessary to initiate incision on the steepening surface. Headcuts (i.e., knickpoints) ultimately form at the downstream end of the sheetflood zones and migrate upstream.

The passage of a headcut through a particular reach and its evolution into a sheetflood zone over time can be thought of as a series of changes in channel type within the Rosgen (1996) classification system. The same channel types can be observed laterally at the same time within one discontinuity (Fig. 5). A gully or "G"-type stream is present immediately downstream of the headcut. As the channel widens downstream, an "F"-type stream emerges and, in turn, gives way to a "C"-type channel where aggradation occurs. The final stream type present could be considered a "B"-type channel in the form of sheetflood zones, which are more of a distributary channel pattern than a braided one.

Similar to meandering rivers that remain in equilibrium by maintaining the same channel dimensions while migrating across a floodplain, discontinuous ephemeral streams can also be considered to be in equilibrium as long as the lengths of channelized areas relative to sheetflood zones remain constant. However, since the zones of narrow eroding channels and wider sheetflood zones have a propensity to propagate upstream (Pelletier and DeLong 2004), dramatic temporal and spatial morphological changes should be considered the norm, rather than the exception, even on discontinuous ephemeral stream systems in equilibrium.

The channelized reaches of discontinuous ephemeral stream systems are often referred to as arroyos. Both natural and human disturbances can initiate cut-and-fill cycles, where deep arroyos with vertical banks are incised into the valley floor and then later backfilled (Antevs 1952, Patton and Schumm 1981, Waters and Haynes 2001) in a process similar to the channel evolutionary model for humid-region rivers described above. Continuous arroyos can form on valley floors when a watershed perturbation favors erosion over aggradation, allowing knickpoints to advance headward faster than the aggrading sheetflood zones. This situation can arise with long-term decreases in the sediment:water ratio (Packard 1974) and loss of flow resistance associated with climate change, destruction of vegetation cover, or artificial flow concentration (Cooke et al. 1993). As with channel evolution in humid climates, the vertical walls of the arroyos become unstable when their heights become too great. The narrow arroyos

begin to widen, stream power per unit area is lost, vegetation takes hold in the channel, and an aggradational phase ensues.

Aggradation can continue until the incised channel is completely back-filled and no well-defined channel exists on the valley floor, as was the case for much of the southwestern United States prior to 1850 (Leopold and Miller 1956). Arroyo formation can occur relatively rapidly (i.e., a few years to decades), while the subsequent widening and backfilling are generally amuch slower (i.e., several decades to centuries), with the exact rates dependent on bank composition and other watershed conditions. Stratigraphic exposures along existing arroyo walls contain evidence that arroyo cutting and subsequent filling have occurred several times through-out the past 10,000 years (Waters and Haynes 2001), indicating that natural forces such as climate change can be responsible for channel evolution along discontinuous ephemeral streams (Bryan 1941, Balling and Wells 1990).

Compound Channels

Compound channels consist of a single, low-flow, meandering channel inset into a wider, braided flood zone (Fig. 6) (Graf 1988b). Dramatic channel widening and activation of braided channels accompany extreme flow events; a meandering form develops after a long (i.e., decades) sequence of low to moderate discharges (Kondolf and Curry 1986, Pearthree and Baker 1987, Kresan 1988, Graf 1988b, Friedman and Lee 2002). While similar channel conditions are found in humid climates (Hickin and Sichingabula 1988), compound channel development is enhanced, and their presence more common, in arid climates for at least three primary reasons: the lower density of erosion-resistant vegetation (Graf 1978, Kondolf and Curry 1986), the greater prevalence of non-cohesive sandy soils (Cooke at al. 1993), and a higher ratio between record peak discharges and average annual discharge (Graf 1988b). All of these factors promote rapid channel widening during extreme events.

Rapid widening represents a channel's response to a dramatic increase in sediment transport capacity during an extreme, yet brief, discharge. As channel width increases, sediment transport capacity declines due to the greater hydraulic roughness created by the increasing width:depth ratio, bringing the channel towards equilibrium with the extreme discharge. After the passage of a large flood and the development of a compound channel with multiple braided flow paths, the river system is out of

Figure 6. Compound channel showing single-thread meandering channel inset into a wider braided pattern. (From Graf 1988b.)

equilibrium with the subsequent small to moderate discharges that pass through the system. The smaller flows have insufficient stream power to transport the sediment delivered to the reach when flow is divided between several flow paths. The ensuing aggradation and revegetation begins a self-enhancing process that leads to channel narrowing, increases

in sinuosity, and decreases in the number of active flow paths, resulting in a channel configuration that can more effectively transport the sediment supplied by the smaller discharges. Within the framework of the Rosgen (1996) classification system, this evolutionary trend would represent a conversion of a “B” channel to a “C”-type channel. The narrowing process is accelerated where a reliable moisture supply increases the density and growth rate of vegetation (Friedman and Lee 2002). However, recent flume studies have shown that the sparser vegetative growth in semi-arid and arid climates may actually promote braiding and the development of multiple flow paths (Coulthard 2005). This contrasts with temperate climates, where channels with densely vegetated banks can have widths only half that of sparsely vegetated banks (Hey and Thorne 1986).

The transformations that occur through time along compound channels are in many ways similar to the channel evolutionary process that follows incision on humid-region rivers (Fig. 2) (Simon and Hupp 1986). Because of sandy bank sediments and the lack of dense vegetative growth, an incision phase does not occur along compound channels, and the widening phase is completed in a matter of hours during a single extreme event. The transformation of the channel back to a narrower meandering pattern is akin to the aggradational phase of humid-region rivers. However, lateral, rather than vertical, accretion occurs through the attachment of mid-channel bars to the channel banks by sediment accumulation (Pearthree and Baker 1987). Small to moderate discharge events at this stage can lead to shifts in the position of the low-flow channel due to the build-up of sediment within the channel, potentially leaving evidence of low-flow channels within the entire compound channel. Full recovery and completion of the evolutionary cycle is less likely on compound channels compared to humid-region rivers, because the system is periodically interrupted by large floods that flush out accumulated sediment and rejuvenate the braided form. Since vegetative growth can better withstand erosive forces, humid-region rivers are less responsive to extreme events and less likely to develop, or maintain, a compound channel form. The lack of vegetation on arid-region rivers also hinders the development of a vertically accreting floodplain, so flow energy is dissipated within the channel through bank erosion rather than by spreading across a broad overbank surface.

Alluvial Fans

Alluvial fans are depositional landforms with a conical shape that develop where confined streams emerge from upland areas into zones of reduced

stream power (Fig. 7) (Harvey 1997). While alluvial fans are found in almost all climates (Nilsen and Moore 1984, Rachocki and Church 1990), they are an especially important landscape element in the Arid West, where an estimated 31 percent of the land surface is covered by alluvial fan deposits (Antsey 1966). Various stream system types can be active on alluvial fan surfaces, including those discussed above: meandering rivers (McCarthy et al. 1992), discontinuous ephemeral streams (Field 2001), and compound channels (Scott 1973). Debris flows, not discussed in detail here, are also important in alluvial fan development (Blair and McPherson 1992, Whipple and Dunne 1992). What gives rise to the characteristic fan shape of these landforms is the propensity for channel avulsions (i.e., rapid changes in channel position) on the unconfined surfaces. Found at the junction of erosional mountain headwaters and depositional valley bottom streams or playas, alluvial fans are aggradational features. Deposition is enhanced on alluvial fans, because stream power is rapidly attenuated as the result of at least three factors, a combination of which may be important on any given fan: a decrease in slope as flows leave the mountains and emerge on the valley floor, a loss in flow confinement as flows emanate from the confined mountain valleys, and a loss of discharge through transmission losses into permeable alluvial soils after debouching from the impermeable bedrock mountains.

Figure 7. Conical shape and distributary flow pattern developed on an alluvial fan at Badwater, Death Valley, California. (Used with permission of Marli Bryant Miller at www.marlimillerphoto.com.).

The aggradational nature of alluvial fans drives an evolutionary process that culminates in channel avulsions (Fig. 8) (Field 2001). Overbank flows emanating from channels on the fan surface are relatively devoid of sediment and are capable of carving gullies, or “G”-type channels, on the fan surface when the flow becomes reconcentrated (Fig. 8a). As deposition continues in the main channel, decreasing bank heights, additional overbank flow is generated that accelerates the creation of the gullies and their advancement towards the main flow path. Eventually the main flow path is abandoned during a large storm event and switches into one of the gullies draining the fan surface, which at this stage has a lower bed elevation than the previously active flow path (Fig. 8b).

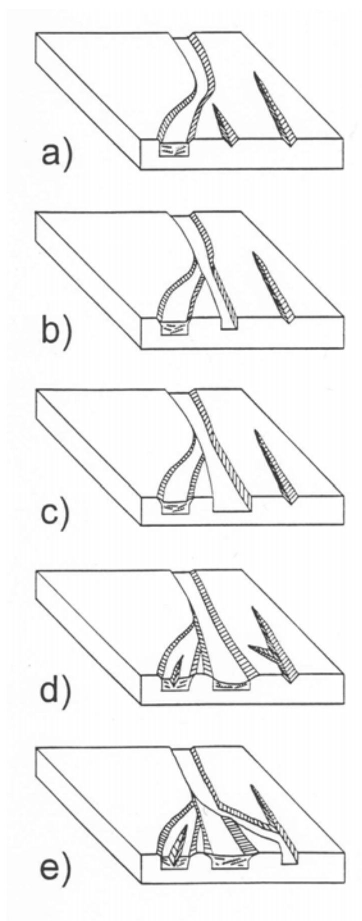


Figure 8. Model of channel evolution on alluvial fans. See the text for a description of the stages. (From Field 2001.)

The channel morphology of the gully that captured flow during the avulsion begins a transformational process in response to the increased discharge and sediment loading delivered from the upper watershed to which it is now directly connected. To reach equilibrium with the greater discharge, the channel grows in size through widening of non-cohesive sandy banks (Fig. 8c) to create an “F”-type channel. Widening continues until the flow magnitude needed to further enlarge the channel occurs too infrequently to counteract the aggradational tendencies of lower-magnitude flows. The smaller flows are unable to completely transport sediment through the widened channels, and deposition in the channel begins (Fig. 8d). As the conveyance of the channel decreases with aggradation, greater and greater amounts of overbank flow are generated along what has become a low-sinuosity “C”- or “B”-type channel. The overbank flow is reconcentrated into gullies heading on the fan surface, causing gully enlargement and headward migration towards the source of overbank flow. Portions of previously abandoned channels can also become incised as overbank flow enters these lower areas on the fan surface. Ultimately, a channel avulsion results when the lengthening gully reaches the main channel and the majority of flow is once again shifted into a new flow path (Fig. 8e).

Not only do the evolutionary processes described above take place at a single location through time, but all stages of channel evolution can be present at different locations on the fan surface at the same time. Since each stage of the evolutionary process is characterized by a distinct channel morphology (Fig. 9), a variety of physical features can persist on an alluvial fan for long periods of time, despite constant changes in their location. This diversity of features gives rise to numerous habitats, supports a complex ecosystem, and sustains healthy stream function despite frequent and rapid changes in channel position.

Many of the evolutionary stages leading to channel avulsions on alluvial fans are similar to channel evolution processes on humid-region meandering rivers. Immediately following an avulsion, the new channel has a low width:depth ratio and steep vertical banks like recently incised channels (compare Fig. 2b and 8b), although arid-region alluvial-fan channels with non-cohesive sandy banks are likely much shallower for a stream of the same size. The subsequent widening phase is similar both in process and form (Fig. 2c and 8c). Whereas aggradation along humid-region rivers can lead to the development of a stable, vertically accreted floodplain surface,

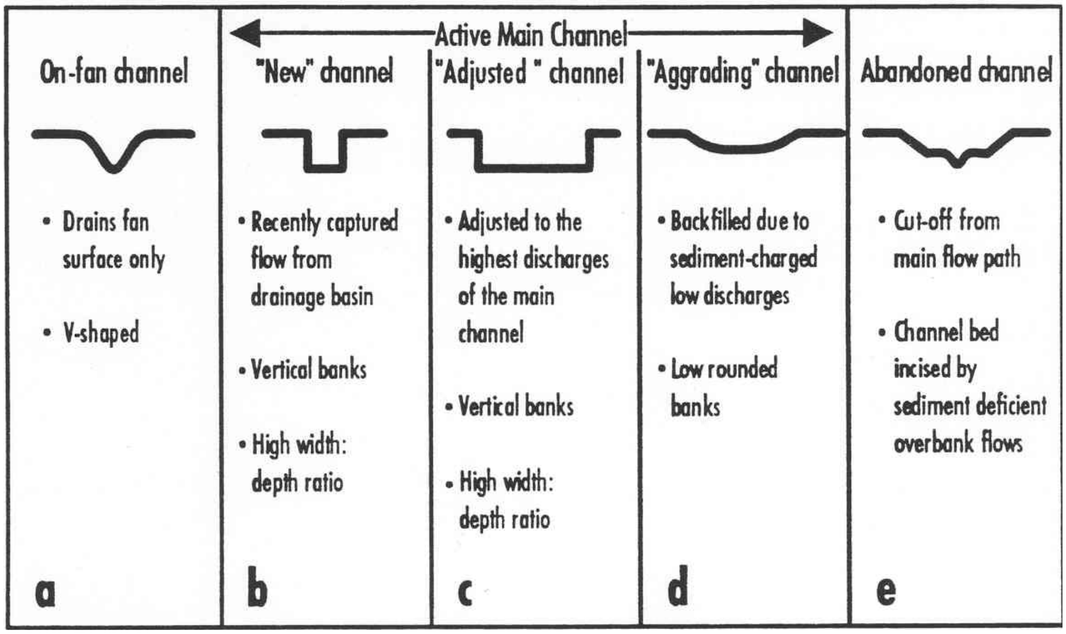


Figure 9. Five channel morphologies observed on alluvial fans in southern Arizona. Note that a single channel reach can go through each phase of channel development through time and that each stage of development may be observed in different places on a fan at the same time. (From Field 2001.)

deposition leads to instabilities on broad, unconfined alluvial fans. The build-up of sediment in the active flow path on an alluvial fan creates a localized increase in slope that deflects flow elsewhere. Channel avulsions preferentially result in channel migration towards lower portions of the fan, allowing for the long-term build-up of the fan surface. The long-term vertical accretion of a broad fan surface requires a continuing series of avulsions, each the culmination of an evolutionary process (Fig. 8). In contrast, the vertical accretion of a floodplain surface in a more confined valley can occur as part of a single evolutionary cycle (Fig. 4), especially in humid regions where riparian vegetation traps additional sediment and debris.

Anastomosing Rivers

Anastomosing rivers are sinuous, low-gradient channels consisting of multiple interconnected branches transporting a suspended or mixed sediment load of fine-grained sediments (Fig. 10) (Schumann 1989). In plan view, the splitting and rejoining of anastomosing channel branches appear similar to braided channels, but many distinct differences exist (Fig. 6 and 10). Whereas flow is fairly evenly divided amidst different braided flow paths, one main channel is characteristic of anastomosing channels, with

Figure 10. Anastomosing channels along Cooper Creek, Australia. The primary channel active during low flows runs from left to right across the center of the photo. (Copyright, Colin P. North, University of Aberdeen, Scotland; used by permission.)

only overbank flow feeding smaller anabranches. Given the high suspended load content and fine-grained bank material, channel width:depth ratios are lower and sinuosities higher than for braided rivers. Also, channels persist in the same positions for longer periods of time. Anastomosing channels from Australia form in sand-bed rivers where vegetation serves as a stabilizing influence (Wende and Nanson 1998, Tooth and Nanson 2000b). As vegetation density increases, channel position can become stabilized while maintaining multiple flow paths (Coulthard 2005). In other words, a braided configuration with rapidly shifting channel positions can transform into an anastomosing pattern with sufficient vegetation. Anastomosing rivers are present in the Arid West (Schumann 1989, Malisce 1993) but are not common, given the necessary prerequisites of high suspended load and/or dense vegetation.

Channel avulsions frequently occur on anastomosing rivers in a process similar to the one described above for alluvial fans (Schumann 1989). Smaller anabranch channels grow headward towards the main channel in response to overbank flows emanating from the aggrading main channel. The widening stage that occurs on alluvial fans with non-cohesive sandy soils is somewhat muted on anastomosing rivers, given the more cohesive bank materials and/or bank vegetation present. The low width:depth

ratios of anastomosing channels are similar to channels during the incised phase of humid-region channel evolution models (Fig. 2b). However, before a widening and aggradational phase can be fully completed, overbank flows from the channel lead to an avulsion that creates a new channel with a low width:depth ratio. Unlike in humid regions, a stable, vertically accreted floodplain is not the end result of channel evolutionary processes on anastomosing rivers. Instead, a landform punctuated in time by avulsions creates a stream system with a range of morphological features and, consequently, physical habitats. As on alluvial fans, the dramatic temporal and spatial changes in channel morphology and position associated with channel avulsions should be considered the norm, rather than the exception, on anastomosing rivers.

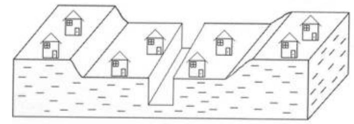
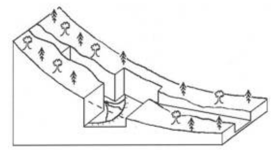
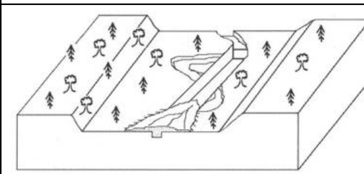
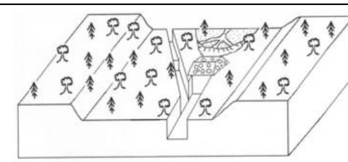
4 Human Impacts on Channel Morphology

The morphological conditions and evolutionary changes that characterize the different stream types described above can all result from natural watershed conditions. Human-induced channel responses pass through similar evolutionary stages in each stream type, but the spatial distribution and rate of evolutionary processes may differ from natural conditions. Natural or human disturbances that alter equilibrium conditions and initiate a process of channel evolution can result in the loss of stream function. Although volcanic eruptions are a notable exception, natural perturbations are often not significant enough to cause a permanent departure from equilibrium conditions (e.g., a large flood) or, when significant, they occur over long enough time scales to provide sufficient time for stream and ecosystem functions to adapt to the changing equilibrium conditions (e.g., climate change). In contrast, human perturbations can cause rapid and permanent changes to equilibrium conditions such that stream function and ecosystem health are unable to recover on time scales of concern to river managers (i.e., decades).

Understanding channel response to human impacts is important, because the type, distribution, and distinctiveness of physical features and stream functions present at a particular location may be altered by human-induced adjustments to channel morphology. Although an almost limitless number of combinations of human land uses can precipitate a channel response, five human activities have been responsible for significant channel adjustments in the Arid West, both in terms of the magnitude of change on a particular stream and their widespread occurrence throughout the region: land clearance for agriculture, urbanization, gravel mining, channelization, and dam construction. The typical channel response to each of these activities, at least when considered in isolation, is fairly well understood as described below and is summarized in Table 1.

Responses to human activities take place not only at the site of the disturbance, but also potentially upstream and downstream as adjustments propagate through the system to minimize changes at any one point. Morphological adjustments resulting directly from human impacts have long been recognized, while the less obvious impacts occurring off-site are much more recently appreciated (Gregory 2006). Channel adjustments,

Table 1. Typical channel responses to common land uses in the Southwest.

Land Use	Response			Sketch	Change in OHW function
	Upstream	At site	Downstream		
Land Clearing 	Erosion as head-cut migrates upstream if incision occurs at site	Erosion if limited sediment supply as in Arid West but deposition in temperate climates	Deposition as excess sediment is delivered from upstream		Loss of floodplain attenuation with incision Increased sediment delivery and flooding downstream Floodplain vegetation stressed as water table drops with incision
Urbanization 	Erosion as head-cut migrates upstream	Erosion as impervious surface area increases	Deposition as excess sediment is delivered from upstream		Increased peak flows Loss of floodplain storage with development and attenuation with incision
Gravel Mining 	Erosion as head-cut migrates upstream from mining site	Deposition due to loss in transport capacity on lower gradient or in wider channel	Erosion due to “hungry water” as sediment load is deposited at the site		Loss of fine sediment deposition on floodplain downstream Loss of floodplain access at site and upstream
Channelization 	Erosion as headcut migrates upstream	Erosion due to increased gradient and decreased roughness	Deposition as excess sediment is delivered from upstream		Increases stream power in channel Loss of floodplain attenuation with incision Increased sediment delivery and flooding downstream
Dams 	Deposition in impoundment	No response assuming dam is not breached	Erosion due to “hungry water” as sediment load is deposited in the impoundment		Channel and floodplain inundation upstream Loss of fine sediment deposition on floodplain downstream

whether to natural or human perturbations, are ostensibly dictated by changes in the sediment:water ratio of floodwaters or, more accurately, by changes in the balance between the sediment delivered to the reach and the stream's capacity to transport the sediment. Aggradation occurs when the sediment delivered to the stream exceeds the capacity of the flowing water to transport the sediment, reflecting an increase in the sediment:water ratio. In contrast, a decrease in the sediment:water ratio leads to incision. After a critical threshold in the sediment:water ratio is crossed and incision or aggradation begins, each stream type described above undergoes a sequence of similar, yet unique, evolutionary changes that alter the sediment:water ratio in such a way that brings the channel into equilibrium with the new prevailing conditions.

Land Clearance for Agriculture

Before the widespread introduction of cattle in the 1800s, many valley bottom settings in the Arid West were characterized by thick vegetation and cienegas (i.e., spring-fed wetlands) supported by a high water table. Channels were typically unconfined and shallow, with multiple anastomosing flow paths likely developing in areas with dense vegetative growth, while compound channels or discontinuous ephemeral streams predominated elsewhere. A period of arroyo cutting in the late 1800s is believed by many researchers to be the result of overgrazing by cattle (Antevs 1952, Bull 1997), while others have considered natural changes in rainfall intensity another likely cause (Bryan 1941, Waters and Haynes 2001, Gellis et al. 2005).

For at least some watersheds, the loss of vegetative cover in the Arid West associated with overgrazing made the exposed soils less resistant to the erosive forces of floods, leading to incision of the valley bottoms. This began a cycle of arroyo cutting that concentrated previously unconfined flows on the valley bottoms into confined steep-walled arroyos. Greater stream power was focused on the channel bed, leading to further incision. Downcutting of the valley floors also caused a drop in the water table and placed additional stress on whatever stabilizing vegetation was present. Thus, the initial response to the overgrazing started an cyclic feedback loop that, for a short period, furthered the incision as less and less flow-baffling vegetation was present to trap sediment. Eventually, however, as the slope was reduced by incision, further stream power was lost by widening, and sediment production from the steepening banks accelerated, the sediment:water ratio of the flows increased to the point where a long

period of aggradation began. Many of the arroyos incised in the 19th century have backfilled in the 20th century as channel evolution has progressed to its final stages (Emmett 1974). However, arroyos are still present in other watersheds that have not yet fully adjusted to the initial overgrazing more than 150 years ago.

Land clearing in temperate climates has often resulted in an opposite river response, with extensive aggradation occurring on valley bottoms after erodible soils on adjacent hillslopes were exposed by deforestation (Costa 1975, Trimble 1983, Bierman et al. 1997, Karwan et al. 2001). Incision of the aggraded sediments generally occurs after sediment is depleted or is again anchored to the hillslopes with reforestation (Kondolf et al. 2002a). Increases in peak discharge, as occur with the loss of vegetation on hillslopes, result in an exponentially greater increase in sediment transport capacity (Bull 1979). Consequently, in temperate climates, where ample sediment is generally available for transport, the resulting increase in the sediment:water ratio of flood flows leads to aggradation. In contrast, a lack of available sediment in arid climates means that increases in peak discharge associated with land clearance are not accompanied by exponentially greater increases in sediment load. The transport capacity of the flows, therefore, increases relative to the sediment load available, resulting in incision.

Aggradation can still occur with land clearing in the Arid West in settings where ample sediment is available for transport. Such conditions were created in California, just outside the area of study (Fig. 1), on streams impacted by hydraulic placer mining where high-pressure water cannons were used to dislodge older terrace deposits of gravel. Gold was removed as the sediment was sent through sluices and discharged directly in the river channel (Mount 1995). Channel aggradation has occurred for miles downstream as a result of the elevated sediment load. The sediment moves downstream in waves, causing increased rates of bank erosion and channel migration where rivers have lost confinement through channel infilling (James 1999, Kondolf et al. 2002a, Wohl 2005).

Urbanization

Urbanization has had an increasingly important impact on rivers in the Arid West. Several conditions accompanying urbanization lead to channel incision (Dunne and Leopold 1978, Booth 1990, Doyle et al. 2000) and enlargement (Hammer 1972, Graf 1975, Dunne and Leopold 1978, Gregory

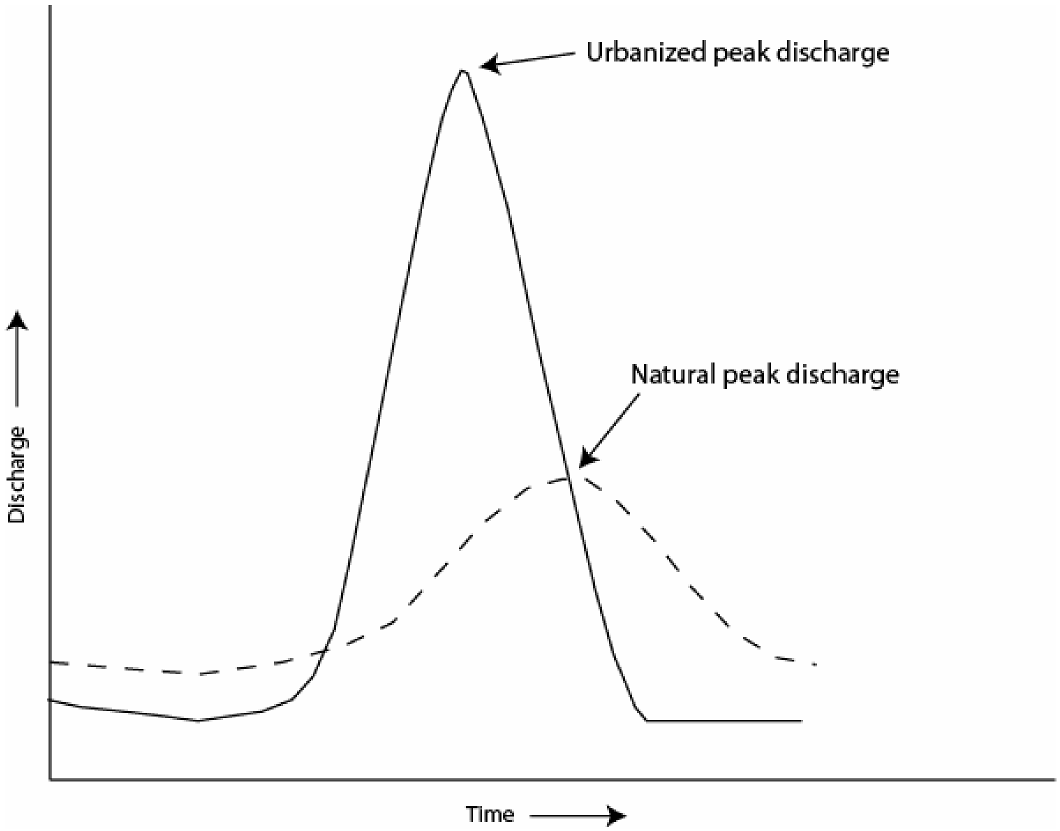


Figure 11. Simplified hydrographs showing the difference in peak discharge in the same watershed for a similar rainfall event before and after urbanization.

et al. 1992, Pizzuto et al. 2000, Booth et al. 2002). Peak discharges for the same rainfall event are generally larger in an urbanized environment (Fig. 11), because of several factors: increases in impermeable surface area, reconfiguration and shortening of the drainage network with storm sewers, loss of floodwater storage as wetlands are filled, and smoothing of the land surface (Leopold 1968). In the Arid West, overpumping of groundwater for municipal, agricultural, and industrial uses has lowered the water table in many basins by hundreds of feet. As a result, stabilizing plants, with their primary source of soil moisture no longer accessible, have died back over the last several decades (Fig. 12) or never fully recovered from earlier overgrazing. Bank armoring, along with other erosion and flood control efforts, has further constrained flows and promoted incision in urban settings. Channels in smaller watersheds are particularly responsive to urbanization, since a greater percentage of the total drainage area is likely to be impacted, as has been demonstrated in the Arid West (Dunne and Leopold 1978, Chin and Gregory 2001) and elsewhere (Booth 1990). However, channel response, even in intensively urbanized areas, can be minimal where bedrock outcrops, coarse bed and

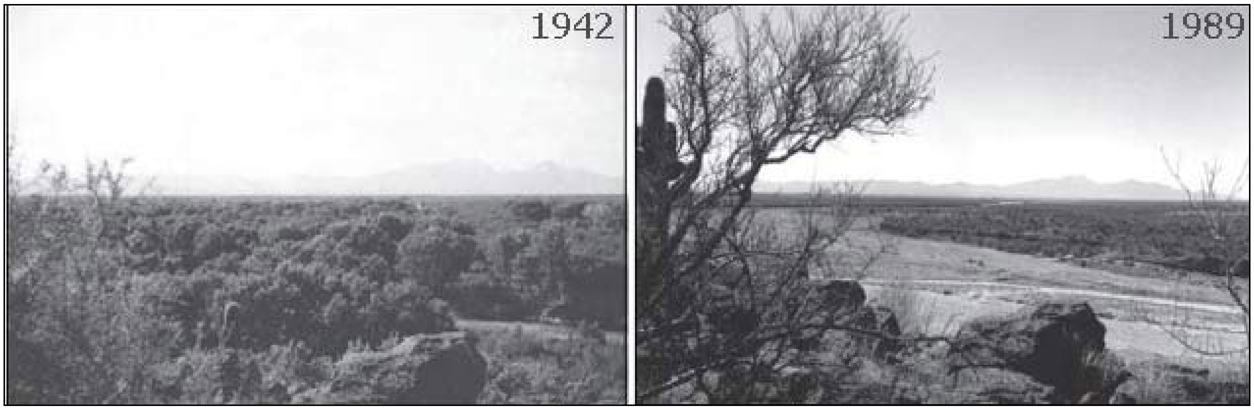


Figure 12. Vegetation changes along the Santa Cruz River near Tucson, Arizona, as a result of a lowering of the water table accompanying ground water withdrawals.

bank material, or other geological controls are present along the stream (Nelson et al. 2006).

The initial build-out phase of an urbanized watershed generally results in higher sediment delivery to the stream channel and aggradation followed by a reduction in sediment supply and incision as impervious surface areas increase peak flows and reduce the available sediment sources exposed during construction (Wolman 1967). Widening and channel enlargement would be expected to follow an initial period of incision as channel evolution progresses. However, channel widening can ensue almost immediately along ephemeral streams, where banks tend to be less resistant to erosion (Chin and Gregory 2001). Given the permanent effect of an increased impervious surface area on peak discharges, channel evolution may not lead to aggradation in the directly affected area where stream power remains high and can maintain the enlarged channel. In arid climates in particular, urbanization has the effect of accentuating the role of extreme events, leading to even longer recovery times (Chin and Gregory 2001). Sediment flushed from urbanized tributaries could lead to channel aggradation farther downstream if the larger watershed is not as densely developed. High sediment transport rates in arid climates (Chin and Gregory 2001) suggest that the likelihood of aggradation downstream of urbanized areas is greater in the Arid West.

Whether urbanized stream channels ever achieve an equilibrium condition remains an open question (Grable and Harden 2006). Continuing development over decades in a watershed can sustain channel adjustments through intermittent new disturbances that change patterns of stormwater runoff and sediment inputs (Grable and Harden 2006). A simplistic chan-

nel evolutionary response to increased peak runoff from urbanization is further complicated by in-stream activities such as channelization, bank armoring, and road crossings that fragment the adjusting channels into segments undergoing different responses (Chin and Gregory 2001, Grable and Harden 2006). Even where urbanized channels approach an equilibrium state after a period of channel evolution, they likely remain sensitive to large discharges for long periods, because channel enlargement limits floodplain access and the ability to effectively attenuate stream power.

Portions of discontinuous ephemeral streams near the threshold for incision are likely to undergo arroyo cutting in response to urbanization. Since their headward migration will probably exceed the rate at which aggradational areas are migrating upstream, given the decreases in the sediment:water ratio of floodwaters in the urbanized setting, the percentage of channelized flow is likely to increase relative to sheetflood zones in urbanized areas. Compound channels, in contrast, are likely to respond with greater and more frequent periods of widening in response to urbanization. Channel evolution is unlikely to progress completely to a meandering planform because of the increased frequency of higher peak discharges. OHW channel features and functions associated with meandering planforms would be less common in an urbanized setting and replaced by those characteristic of braided systems.

Gravel Mining

Human development of the Arid West has created a large demand for sand and gravel to construct homes, roads, and other infrastructure. The cheapest location to mine this resource is usually from rivers, because the sediment is pre-sorted and close to construction areas on flat valley bottoms and piedmonts, thereby reducing transportation costs. The removal of gravel from rivers, however, changes the channel gradient and precipitates a channel response that migrates upstream and downstream (Fig. 13). While deposition typically occurs at the mining site because of the reduced gradient and flow expansion, erosion is the typical response upstream and downstream of the mining site (Bull and Scott 1974, Kondolf 1994, 1997, Petit et al. 1996, Kondolf et al. 2002b). Upstream erosion occurs as the vertical headwall of the mining site migrates headward (Fig. 13). The knickpoint or headcut, over 10 feet high in some instances (Bull and Scott 1974), remains vertical in more competent bed sediments (Fig. 13b), while the slope lays back more quickly in looser sands and gravels. In either case, the developing arroyo increases sediment delivery downstream such

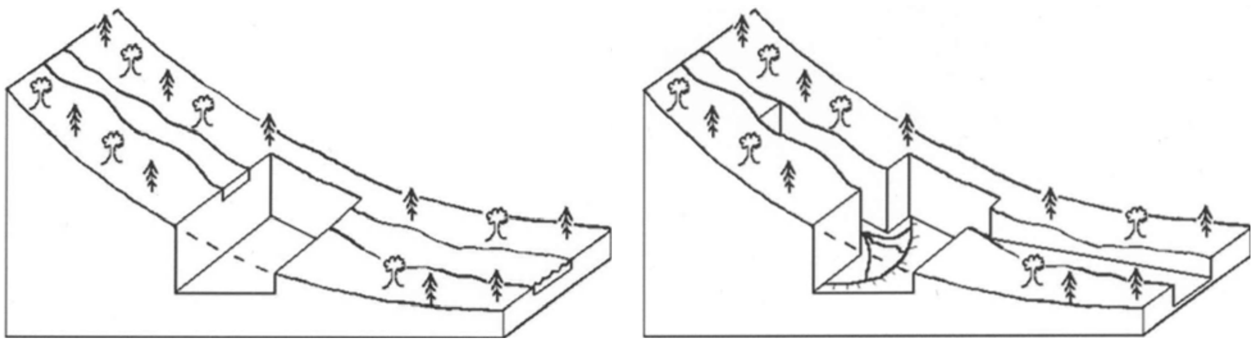


Figure 13. Longitudinal profile of a stream channel immediately after gravel mining completed (left) and following the stream channel response to mining (right). See the text for further description.

that the river's bed elevation trends towards its pre-disturbance condition at the mining site. As the channel upstream undergoes channel evolution and, in turn, responds to the increasing bed elevation at the site, the incised arroyo will widen and backfill and, over time, approach the original bed elevation, assuming no further disturbance occurs.

Bar scalping, whereby a gravel bar is removed, does not lower the channel bed, but the resulting increase in channel cross-sectional area does result in an increase in energy gradient as flood flow velocities are reduced when entering the "scalped" and widened area. Therefore, erosion does occur upstream, but it is focused more on the banks rather than the bed, as the channel minimizes the rate at which channel flow expands into the area widened by the bar scalping. A reduction in stream power per unit area within the scalped area leads to deposition and, ultimately, regrowth of the gravel bar removed by scalping.

The deposition of sediment at the mining site creates a sediment deficit or a "hungry water" effect downstream (Kondolf 1997). The decrease in the sediment:water ratio downstream, due to sediment deposition within the mining site, results in erosion until enough sediment is recruited from the bed and banks to offset the deficit and match the river's transport capacity. The erosion brings the stream back into equilibrium by not only supplying sediment to the channel, but also by reducing the channel gradient and increasing the channel width—two changes that reduce the river's transport capacity. In sandier soils, bank widening will be more important than channel incision. If mining ceases and the bed elevation at the mining site eventually returns to its original condition, the resulting increase in sediment delivery downstream will reverse the downstream response. Channel

aggradation will slowly increase the bed elevation and constrict the channel as the predisturbance channel morphology is re-established.

If the amount of gravel removed is much greater than the rate at which gravel is replenished from the upper watershed, the channel response to gravel mining can last for decades, extend great distances downstream, potentially transform the type of stream system present, and permanently alter stream system function. In western Washington, intense gravel extraction at several times the replenishment rate has led to erosion more than 2.0 miles downstream, whereas impacts were confined to within one or two bars downstream when the amount of gravel extraction was roughly equivalent to the replenishment rate (Dunne et al 1980). In the Arid West, anastomosing or compound channels that typically have several channel threads over a wide swath of the valley bottom could be converted by intense mining into a single-thread channel occupying a narrow arroyo formed by a headcut migrating upstream from a deep gravel pit (Fig. 14). Similarly, disconnected eroding channels along discontinuous ephemeral stream systems (Fig. 5) would join together as a single arroyo as a headcut migrates upstream from a mining site through several sheetflood zones, confining flow along much longer reaches than naturally occur. As sheetflood zones and channels with multiple flow paths are confined to a single deep arroyo, features formed on frequently flooded surfaces might be obliterated by encroaching vegetation and replaced by new features reflecting the altered flow conditions. The functional value of such surfaces as areas of flow energy attenuation and for supporting unique physical habitats would also be lost.

Once incision is initiated upstream and downstream of a mining site, a mining operation that is active for only a short time can be responsible for a series of evolutionary changes that last much longer. The evolution towards a predisturbance condition will continue until sediment delivered from the upper watershed replenishes the amount removed. Channel adjustments might be expected to persist longer in the Arid West, where the frequency of sediment-transporting events is much lower. The time needed for channel evolution to be completed and equilibrium re-established is also related to the scale of previous mining operations. Consequently, site-specific studies of mining history in any given watershed would be critical for identifying the existing OHW functions and determining how those functions are changing with the continuing channel adjustments.

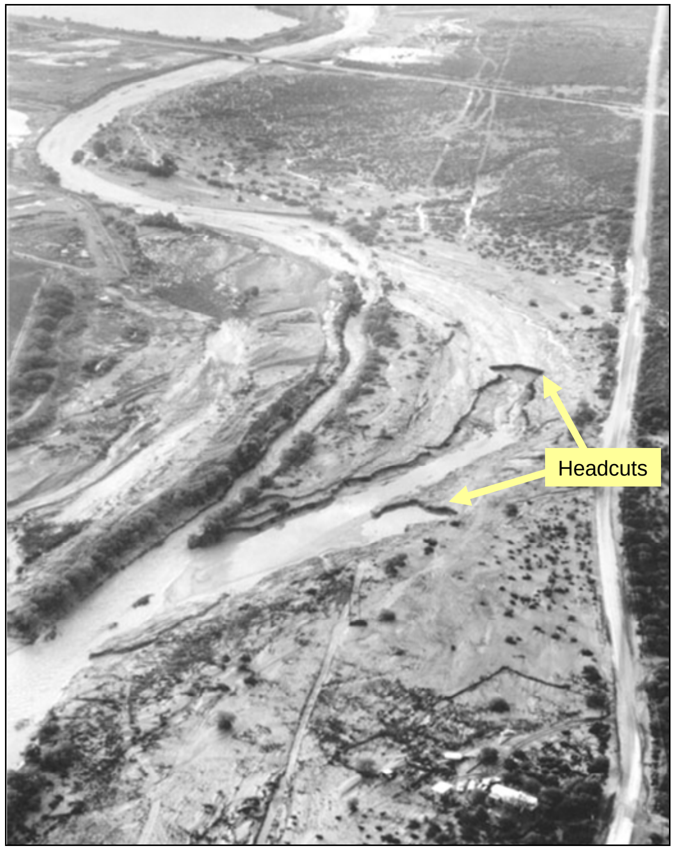


Figure 14. Headcuts formed by 1983 flood on Santa Cruz River in Tucson, AZ. Similar headcuts form upstream of gravel mining operations. Photograph taken October 4, 1983, looking upstream. Aerial photograph by Peter L. Kresan (Copyright 1983).

Channelization

Channelization is a general term used to describe a number of river management practices that tend to confine flood flows and reduce flood elevations by increasing the stream's velocity. These practices include channel straightening, debris removal, and bank armoring (with riprap, concrete, or soil cement). The increase in slope and the reduction in hydraulic roughness accompanying channelization increases the stream's sediment transport capacity and results in channel incision (Fig. 15) (Brookes 1985, Rhoads 1990, Hupp 1992, Warne et al. 2000, Simon and Rinaldi 2006). The increase in stream power is initially contained within the altered reach, but the incision propagates upstream as the stream minimizes the rate of change in stream power from point to point. The extent to which a headcut migrates upstream depends on the magnitude of the channelization, with more extensive upstream impacts resulting from greater stream length reduction due to straightening.

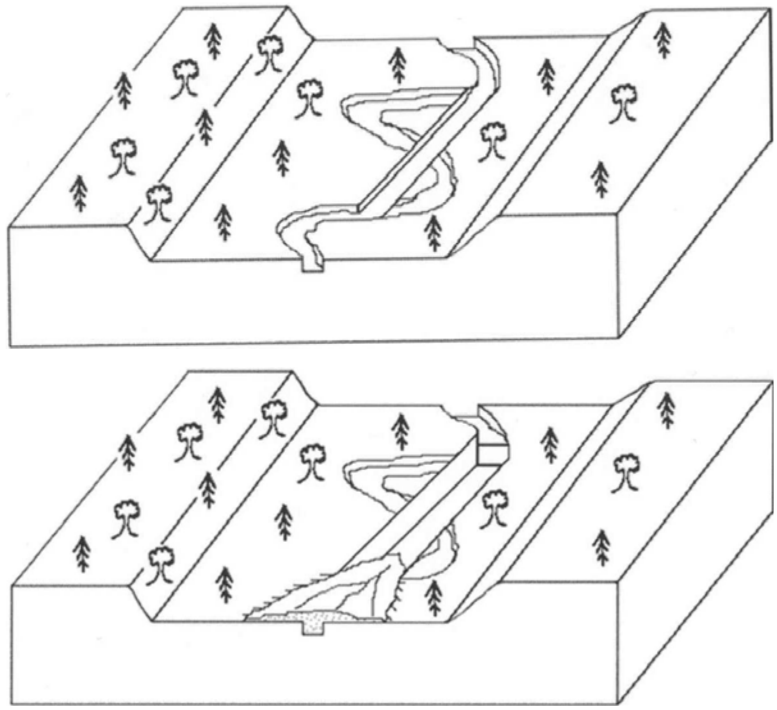


Figure 15. Cross section of a stream valley immediately after channelization is completed (top) and following the stream channel response to channelization (bottom). See the text for further description.

The excess sediment produced by the incision and subsequent widening, as channel evolution progresses, is transported to unaltered reaches downstream. Unable to transport the excess sediment, downstream reaches aggrade and build up a steeper slope more capable of transporting the additional sediment. In compound channels, the aggradation would make the channels more sensitive to large floods and less able to develop or sustain a single-thread meandering pattern. The length of sheet flood zones in discontinuous ephemeral streams is likely to increase relative to channelized reaches, because the excess sediment will accelerate the upstream migration of sheetflood zones while dampening the headward movement of headcuts.

Equilibrium can ultimately return to straightened reaches and affected areas upstream if channel evolution is allowed to proceed without interference. Following the initial incision, a period of widening would create the accommodation space necessary for the channel to begin a period of aggradation that will ultimately lead to the re-creation of meanders that were present before straightening. Downstream, sediment:water ratios will decrease as sediment is stored in the aggrading reaches upstream, and

incision of the recently deposited sediment will return the channel to its original slope and dimensions.

However, a full return to predisturbance conditions following channelization is probably rare. Bank erosion at the onset of widening poses what is generally deemed an unacceptable risk to infrastructure and agricultural land along the river. Bank armoring to stop the erosion has been a common response to widening along channelized reaches (Brookes 1985). By halting the channel evolutionary process, the sediment transport capacity remains high, and sediment continues to move downstream at an accelerated rate, delaying a return to equilibrium elsewhere as well. Downstream reaches undergoing aggradation are often subject to increased flooding as the channels fill with sediment (Brookes 1985). Consequently, these reaches have often, in turn, been channelized themselves to reduce the flooding, effectively transferring the excess sediment even farther downstream. The initial channelization and subsequent management, therefore, result in long-term changes in OHW functions and ecosystem health.

Dam Construction

Dams in the Arid West are important flood control and water supply structures, but channel adjustments result downstream due to changes in hydrology and sediment supply. In general, dams decrease peak flows downstream as water is stored behind the dam and is released slowly over an extended period of time (Williams and Wolman 1984). Although the sediment transport capacity declines with reductions in peak discharge, the sediment:water ratio typically decreases, because most of the sediment load is stored behind the dam. As a result, channel incision is frequently observed downstream of dams (Fig. 16 middle) (Williams and Wolman 1984, Kondolf 1997, Brandt 2000, Phillips et al. 2005). Since a stream's competence to move large particles is reduced with a decline in peak discharge, erosion downstream of dams preferentially removes smaller particles from the channel bed and banks, leaving an armor of coarser particles on the stream bottom (Phillips et al. 2005). The amount and rate of erosion can decline rapidly where the surface armor protects the finer sediment underneath from further scour. The impacts of dams can extend a considerable distance downstream if the sediment deficit is not replaced near the dam because of bed armoring or the presence of erosion-resistant materials (Williams and Wolman 1984).

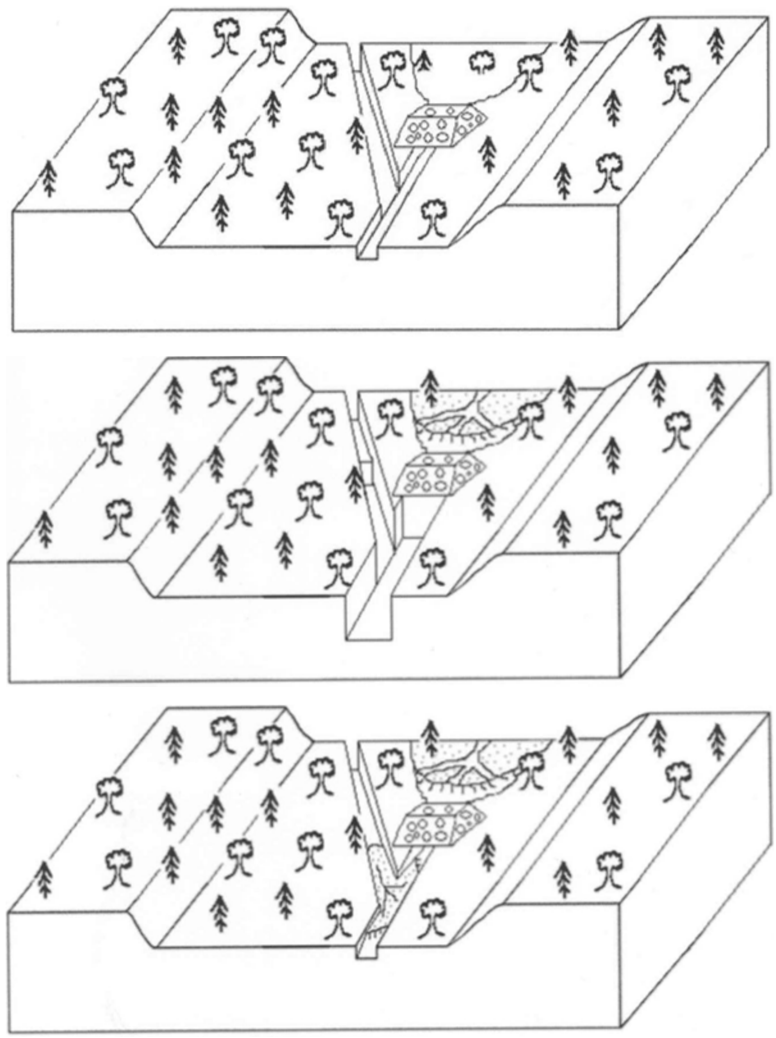


Figure 16. Cross section of a stream valley immediately after dam construction (top) and following the stream channel response if the tributary inputs of sediment are low (middle) or high (bottom). See the text for further description.

The actual character and extent of the channel response downstream of dams can vary dramatically between rivers, given the complex interplay between reductions in peak discharge, loss of sediment load, bank soil composition, contributions from tributaries, and other natural controls (e.g., bedrock outcrops). In wide compound channel systems, channel narrowing often results, because the reduced peak discharges can no longer occupy and maintain the multiple braided flow paths. This leads to a decline in the geomorphic and ecological complexity of the stream system (Graf 2006). Without an ample sediment supply, discontinuous ephemeral streams are also likely to experience narrowing if a greater percentage of the stream's length is converted to channelized flow as the rate of headward-migrating arroyos outpaces the upstream movement of

sheetflood zones. In contrast, single-thread meandering channels where flows are generally more confined can experience widening as “hungry water” scours the banks until the recruited sediment creates a balance with the transport capacity of the stream (Kondolf 1997). The widening would usually follow an initial period of incision, but it can begin more rapidly where non-cohesive sandy soils are present.

The interaction of tributaries can alter the expected downstream channel adjustments (Brandt 2000). When peak discharges are significantly reduced, the flow may be unable to transport the sediment delivered to the channel by tributaries, because the material is either too coarse or too plentiful. The resulting aggradation builds up the channel slope until the stream’s competence and transport capacity are increased sufficiently to entrain the tributary inputs (Fig. 16 bottom). If tributary inputs are insufficient to arrest channel incision downstream of dams, then headcuts can migrate up the tributaries, because of the drop in bed elevation on the main channel (Fig. 16 middle). As the headcut passes through the tributary, the change in slope that is initially focused at the tributary junction is minimized from point to point, and equilibrium re-established throughout the watershed. Headcuts can migrate upstream a considerable distance if bed lowering on the mainstem is significant.

Significantly less research has focused on channel adjustments upstream of dams. As sediment accumulation behind the dam raises the channel’s bed elevation, localized aggradation further upstream should be expected. Tributaries can, in turn, aggrade in response to the rising bed elevation of the mainstem upstream of the dam.

5 Identifying Altered Channel Morphologies on Impacted Rivers

The OHW channel is identified by numerous physical features formed along the channel margins (Table 2). These features are best developed in humid temperate climates where channel morphology is adjusted to the flows most commonly experienced, often referred to as the bankfull flow (Wolman and Miller 1960). The effectiveness of large floods in arid climates, however, means that such morphological features are frequently reworked and are, therefore, less distinctive than in humid climates. The transitory nature of morphological features in arid climates is further enhanced by generally less cohesive soils and poorly vegetated banks.

Table 2. Physical features that have been used to identify bankfull stage.

Bankfull Feature	Reference
Valley flat	Williams 1978
Active floodplain	Williams 1978
Low bench	Williams 1978
Middle bench for rivers with multiple overflow surfaces	Williams 1978
Most prominent bench	Williams 1978
Highest surface of the channel bars	Williams 1978
Lower limit of perennial vegetation	Williams 1978
Upper limit of sand-sized particles	Williams 1978
Top of point bars	Rosgen 1996
Break in slope of banks	Rosgen 1996
Change in particle size distribution	Rosgen 1996
Small benches	Rosgen 1996
Staining of rocks	Rosgen 1996
Exposed root hairs below an intact soil layer	Rosgen 1996

The type, distribution, and distinctiveness of channel features and the magnitude of changes through time and space are potentially altered by channel adjustments resulting from human activities in the watershed. The spatial and temporal extent of the changes depends on both the sensitivity of the stream to change and the magnitude of the human-induced perturbation. Channel adjustments, regardless of whether the cause is natural or human, are largely restricted to three primary processes: incision, widening, and aggradation. The effects that each of these processes

might have on stream morphology and function associated with the OHW channel are described below and summarized in Table 3.

Table 3 Impact of various channel adjustment processes on the type, distinctiveness, and spatial extent of OHW channel features.

Adjustment Process	Changes to OHW Channel			
	Type*	Distinctiveness	Spatial Extent	Comments
Incision	Erosion	More distinct	Narrower zone	- Erosional features (e.g., scour lines) likely to be more dominant than depositional (e.g., gravel bars)
Widening	Destruction	More distinct	Variable	- Features at the margin of the OHW channel likely to be destroyed - Lateral juxtaposition of features within and outside the margins of the OHW channel
Aggradation	Depositional	Less distinct	Wider zone	- Depositional features (e.g., gravel bars) likely to be more dominant than erosional (e.g., scour lines) - Vertical juxtaposition of features typically found within and outside the margins of the OHW channel

Channel Incision

Channel incision generally results in a greater confinement of flow such that floods are restricted to a much narrower area compared to predisturbance conditions and require a much greater magnitude to reach the same height. Consequently, OHW channel features developed in the unaltered stream are not likely to persist at the same height after incision begins. Although many of the weathering features formed above the OHW channel and floodplain, such as rock varnish and desert pavement, take thousands of years to form, vegetation can, in some cases, rapidly colonize sand bars that become less frequently inundated by flood flows following incision. Sharp slope breaks between the OHW channel and floodplain on meandering streams would be subdued by rounding of the upper banks of incising channels. New features developing within the outer limits of the OHW channel would emerge as incision slows and the dominant discharge reaches the same point on the channel banks on a regular basis. However, the original edge of the OHW channel would not be obliterated by incision but only subdued by weathering and the growth of vegetation. Also, during

the period of most rapid incision, the bed level may not be stationary for a long enough period of time to establish vegetation and other flood retention features.

Flood flows within an incised channel have a greater amount of stream power focused in the channel and can lead to greater changes in the channel compared to streams with access to a floodplain or other overbank surface (e.g., an alluvial fan). Consequently, an OHW channel that is incised has a greater likelihood of experiencing dramatic alterations in form and function. Features created by larger, less "ordinary," flood flows will be more able to effect changes along the channel because a greater proportion of stream power will be acting within the margins of the OHW channel.

Of all the arid-region stream system types, compound channels would likely have the greatest impact from incision because extensive inundation during large floods would be greatly curtailed. Not only would the active channel be confined to a narrower area, but the shape and general form of the channel would likely change. With incision, more-permanent vegetation could become established in less-active side channels. Also, erosional features along the channel margins (e.g., trim lines) would become more prevalent and distinctive compared to a complex patchwork of depositional features. The reduction in the spatial extent and complexity of the OHW channel would be further enhanced downstream of dams, because of the added effect of peak flow reductions on inundation area and flood stage (Graf 2006).

On discontinuous ephemeral streams, features diagnostic of the OHW channel (Table 2) are perhaps most likely to form in channelized reaches (Fig. 5). The onset of incision will increase the length of channelized reaches at the expense of sheetflood zones where flow energy is typically expended at a greater rate. Therefore, greater stream power is transferred downstream when a greater length of channelized reaches is present compared to the natural equilibrium state. The concentration of stream energy downstream increases the potential for a further response along what might otherwise be a stream reach in equilibrium. Consequently, human activities along one section of a river system can result in the loss of OHW functions elsewhere in the watershed. The channel evolution that results in a new equilibrium condition involves a series of channel adjustments that play out through both time and space. Human land uses that decrease the sediment:water ratio of flood flows will result in the lengthening of

channelized reaches as headcuts migrate through sediment-starved sheet-flood zones. Vegetation will increase on the less-frequently-inundated sheetflood zones and a clearer distinction emerges between the channel and overbank surfaces. While numerical modeling can demonstrate that the wavelengths of discontinuities (Fig. 5) vary with changing sediment fluxes and discharges (Pelletier and DeLong 2004), specific predictions on how the wavelengths of individual discontinuities or portions of discontinuities will vary with certain levels of watershed disturbance are not yet possible.

Incision on an alluvial fan will increase the channel's capacity to transport sediment across the fan surface, thereby reducing the frequency of avulsions. Similarly, on anastomosing stream channels, flow will be more confined to the main channel with less-frequent overbank flows to enlarge and lengthen anabranches that ultimately capture flow. The absence of periodic disturbances across the fan surface will alter OHW functions, including soil-forming processes, ecosystem diversity, and flood flow attenuation. Avulsions rapidly create new habitat assemblages that change more slowly through time as the channel evolves in response to changes in the sediment:water ratio of floodwaters entering the channel. As avulsions and disturbances of the fan surface become less frequent, more areas are able to reach a climax vegetation stage. The result is a loss of habitat complexity across the fan surface, demonstrating how OHW function can be damaged by human-induced channel incision.

Channel Widening

Channel widening typically follows a period of incision, but it can occur more immediately in response to various human impacts if the channel banks are less resistant to erosion. Widening tends to destroy OHW channel features developed along the channel margins. Bank erosion potentially juxtaposes older surfaces with rock varnish, desert pavement, and salt-split cobbles against depositional features formed within the channel. Widening can cause significant erosion of alluvial soils, sometimes of widely varying age and type, each supporting a different vegetation assemblage and larger ecosystem. Soil erosion can, therefore, lead to long-term losses in OHW functions as the soil-forming processes required to replace the lost soils are slow, particularly in desert regions. The sediment produced by widening and soil erosion is transferred downstream where aggradation can create channel instabilities and exacerbate flooding. The water-holding capacity of a channel increases with widening such that

greater discharges are required to generate overbank flow, stressing the less-frequently-inundated floodplain surfaces. The reduction in moisture can place immediate stress on floodplain plants, while diminished deposition on the floodplain leads to long-term losses in soil fertility associated with the fine sediment deposition.

Widening, as discussed here, is restricted to the main channel and should not be confused with increases in the width of overbank inundation areas accompanying aggradation. Widening within an incised channel, therefore, is likely to sustain the revegetation of floodplains, braided flow paths, secondary channels, and sheetflood zones on meandering rivers, compound channels, alluvial fans, and discontinuous ephemeral streams, respectively. While some OHW functions are developed with the emergence of vegetation, continued confinement of flows during the widening phase means that floodwaters are not attenuated as expected when flow accesses these overbank features. Flow energy, therefore, is not evenly distributed along the length of the stream, and its concentration in downstream reaches may lead to channel instabilities.

Channel Aggradation

Channel confinement is lost during aggradation as bank heights decrease with the infilling of the channel. Aggradation, therefore, can lead to the development of depositional features directly on top of other channel features. For instance, observing a gravel bar directly above desert pavement provides evidence that areas that have not flooded for thousands of years are now experiencing inundation. A similar conclusion could be reached when recent deposition is observed around vegetation, such as a saguaro cactus, that typically grows in areas free from regular flooding. While channel widening, as described above, might create a distinct lateral boundary between areas definitively above and below the OHW channel, aggradation is likely to create vertical juxtapositions between features and diffuse lateral boundaries. Depositional features will not be as well developed at the edge of an aggradational zone where bars are smaller, thinner, and less continuous. Given the lack of significant relief on some broad piedmonts between active areas and those that have not flooded for thousands of years (Pelletier et al. 2005), even a small amount of aggradation could lead to the inundation of wide areas beyond the limits of the OHW channel.

Aggradation enhances the development of compound channels. The loss of flow confinement in the main channel will lead to more frequent flooding and maintenance of braided channels, slowing the development of a single meandering main channel within the compound system. With shorter time intervals between events capable of reactivating braided channel paths, the emergence of climax vegetation assemblages would be thwarted, leading to a loss in OHW channel function. Vegetation throughout the system would be dominated by pioneer species, with ecosystem complexity lost given the absence of climax species.

Aggradation often occurs as a channel evolves towards equilibrium following a period of incision and widening. In such cases, the aggradation is generally confined within the higher banks created by the initial downcutting. However, aggradation in the Arid West can also result from increases in sediment delivery to the channel due to upstream straightening, forest fires, and other anthropogenic causes. In these instances, aggradation can fill the existing channel and spread out over an area much wider than the original limits of the OHW channel. In addition to increased flooding of surrounding areas, older, more-fertile soils might be buried by the deposition of nutrient-poor sediments. This can place additional stress on plant species adapted to older, clay-rich soils that are better able to retain what little moisture is present in the arid climate.

Human impacts leading to excess sediment delivery to discontinuous ephemeral stream systems will favor the growth of sheetflood zones over the development of channelized reaches. Consequently, an array of less-well-developed physical features will be found over a greater area without any clear delineation of the OHW channel. The more distinctive features developed where flow is more confined in channelized reaches would be replaced by more diffuse features as sheetflood zones migrate upstream at a faster rate than channelized reaches. While the increased frequency of overbank flows will lead to the attenuation of flow energy, which will decrease potential hazards downstream, the loss of channelized reaches will potentially exacerbate flood hazards within the aggrading reaches themselves. Land use planning must consider how OHW functions will change with human development of a region. For example, development might be restricted in areas adjacent to discontinuous ephemeral stream systems that are prone to dramatic changes in form and function in response to only minor changes in the surrounding watershed conditions.

6 Discussion

Since incision, widening, and aggradation can result from both natural and human-induced perturbations, determining if alterations to OHW form and function are due to human activities is difficult. Furthermore, channel evolution will potentially result in all three response processes occurring at a single location through time such that the type, distinctiveness, and spatial extent of the OHW channel will be in a state of constant flux.

Certain types or portions of stream systems in arid regions are particularly sensitive to human land use and are, therefore, where the most dramatic changes to OHW channel form and function are likely to occur. Compound channels can experience rapid widening during large floods. Activities such as land clearing that remove bank-stabilizing vegetation are likely to increase the sensitivity of the channel to dramatic widening. Additionally, urbanization is likely to produce a widening response during much smaller, more-frequent rainfall events, because of the increased peak discharge produced in such watersheds. Headcuts represent the point on discontinuous ephemeral streams where the most abrupt slope break is found and a threshold between erosion and deposition is present (Pelletier and DeLong 2004). Subtle changes in sediment:water ratios of floodwaters resulting from human activities will yield responses that will first manifest at headcuts. Alluvial fans are prone to avulsions, reflecting the inherent instabilities in channel position for streams at the junction of steep, confined bedrock mountains and flat, open alluvial valleys. Increases in sediment supply caused by human activities will tend to increase the frequency of avulsions and the likelihood of changing the form and function of the existing OHW channel. Identifying and monitoring sensitive portions of stream systems can provide a means for detecting channel responses to ongoing human activities in rapidly developing portions of the Arid West. With indications of change occurring in a particular location, an effort can be made to understand how the stream system will evolve through time and how to mitigate against the loss of OHW functions expected to accompany the anticipated channel adjustments.

7 Conclusions

A review of the geomorphic literature shows that human impacts often result in a series of channel adjustments that return the stream to a new equilibrium condition. Five human activities are common throughout the Arid West: land clearing, urbanization, gravel mining, channelization, and dam construction. The incision, widening, and aggradation that result from these activities can alter the form and function of the OHW channel. Incision is likely to reduce the lateral extent of the OHW channel and potentially result in the abandonment of the floodplain and other overbank features. Channel widening is likely to lead to the destruction of floodplain features along the margins of the channel. Both incision and widening have the potential for making the OHW channel more distinct as a greater proportion of flow energy is focused within the channel. A decrease in flow attenuation across the floodplain, however, will stress floodplain vegetation while increasing flow energy downstream where flood and erosion hazards could be exacerbated. Aggradation, in contrast, is likely to increase the lateral extent of the OHW channel. While the increased moisture related to additional overbank flooding might benefit existing vegetation, the deposition of nutrient-poor sediments above older, more-fertile soils might have longer-term impacts on OHW functions. Shifts in the channel position and evolution of channel morphology in response to human impacts means that the location of the OHW channel and related functions are in even greater flux than under natural conditions. Efforts to manage and protect OHW functions in the Arid West will depend on distinguishing between human and natural adjustments and appreciating the transitory nature of the OHW channel through time and space, even under natural conditions.

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Glossary

Aggradation – An increase in the channel bed elevation through deposition of sediment

Alluvial fan – Depositional landform with a conical shape that develops where confined streams emerge from upland areas into zones of reduced stream power

Anastomosing river - Sinuous, low-gradient channels consisting of multiple interconnected branches transporting a suspended or mixed load

Arroyo - Entrenched ephemeral streams with vertical walls that form in desert environments

Bankfull stage – River level that completely fills the channel and begins to spread out onto the floodplain; sometimes alternatively considered the 1.5-year recurrence interval flow even if not associated with incipient inundation of floodplain

Channel avulsion - Rapid diversion of flow from one channel into another

Compound channel - Channels with a single, low-flow meandering channel inset into a wider braided flood zone active only during extreme events

Desert pavement – Tightly interlocking gravel at the surface formed after years of surface exposure in the absence of active streamflow over the surface

Discontinuous ephemeral stream - A distinctive stream pattern characterized by alternating erosional and depositional reaches

Equilibrium – A balance between sediment and water supply resulting from adjustments of the river channel’s shape, planform, and gradient

Ordinary high water mark - The line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, or the presence of litter and debris

Perturbation – Change in watershed conditions, such as percentage of forest cover, significant enough to engender a channel response

Rock varnish – A dark manganese oxide coating that develops on the outer surface of rocks exposed at the surface and becomes increasingly dark with exposure

Sheetflood - Sheet of unconfined flood water moving down a slope

Trim line - A line along a stream bank below which erosion by flowing water is readily apparent; the feature is usually characterized by a small notch on the bank

Transmission loss – Decrease in discharge in a downstream direction due to infiltration of water into the channel bed; especially pronounced in arid climates

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14. ABSTRACT
Parallel to ongoing efforts to revise the U.S. Army Corps of Engineers wetland delineation manual for support of Section 404 under the Clean Water Act, the Corps has initiated an effort to develop an "Ordinary High Water " (OHW) delineation manual. The Arid West region is dominated by watersheds with intermittent and ephemeral dry washes. Consequently, many aquatic resources lack the three characteristic features of a wetland, but they still perform important wetland functions. Arid West channels have recently been described as "ordinary" when they typically correspond to a 5- to 8-year event and typically have an active floodplain with sparse vegetation cover, shifts in soil texture, and occasional alignment with distinctive bed and bank features. With a better understanding of the stream dynamics associated with regulated "ordinary" events, the Corps is now developing OHW functional models for intermittent and ephemeral stream channels of the Arid West. It cannot be adequately determined if a channel has been altered by human disturbances without an understanding of how channels naturally respond to geomorphically effective events and evolve through time. This report provides a literature review of natural and human controls on fluvial processes in the Arid West.

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